LA-UR-17-21904

Title: Space Nuclear Reactor Development

Author(s): Mcclure, Patrick Ray

Intended for: Nuclear Engineering Capability Review

Issued: 2017-03-06

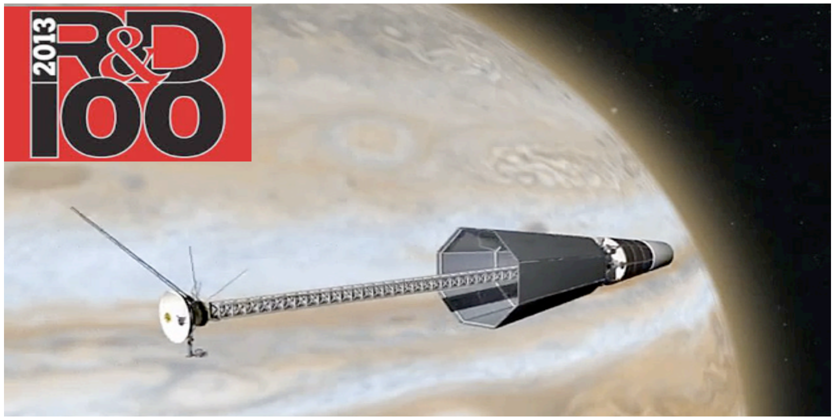
Space Nuclear Reactor Development

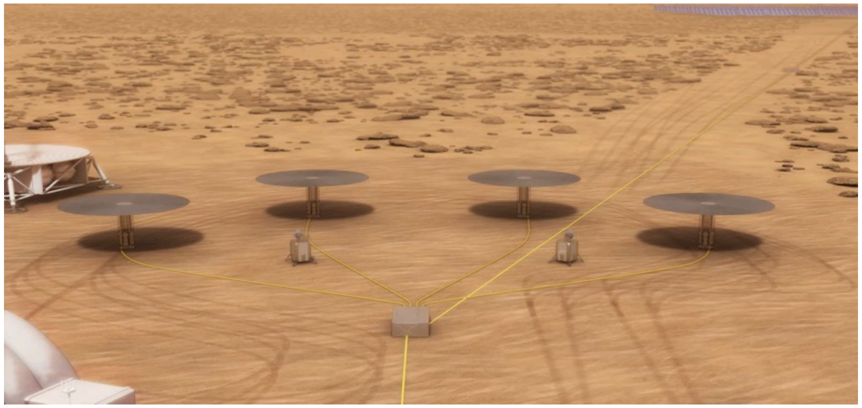
Nuclear Engineering Capability Review

Patrick McClure, NEN-5

March, 2017

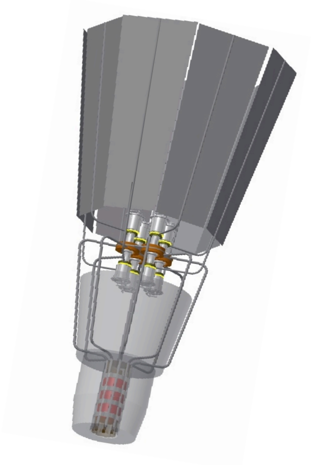
The KiloPower Space Reactor Concept





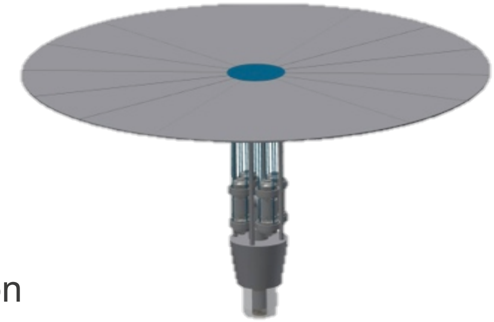
Attributes:

- Scalable 1-10kWe (4-10kWt)
- All Passive Heat Transfer
- Stirling Power Conversion
- UMo cast metal fuel
- Low Fuel Burnup
- Low startup power
- Start/Stop operation

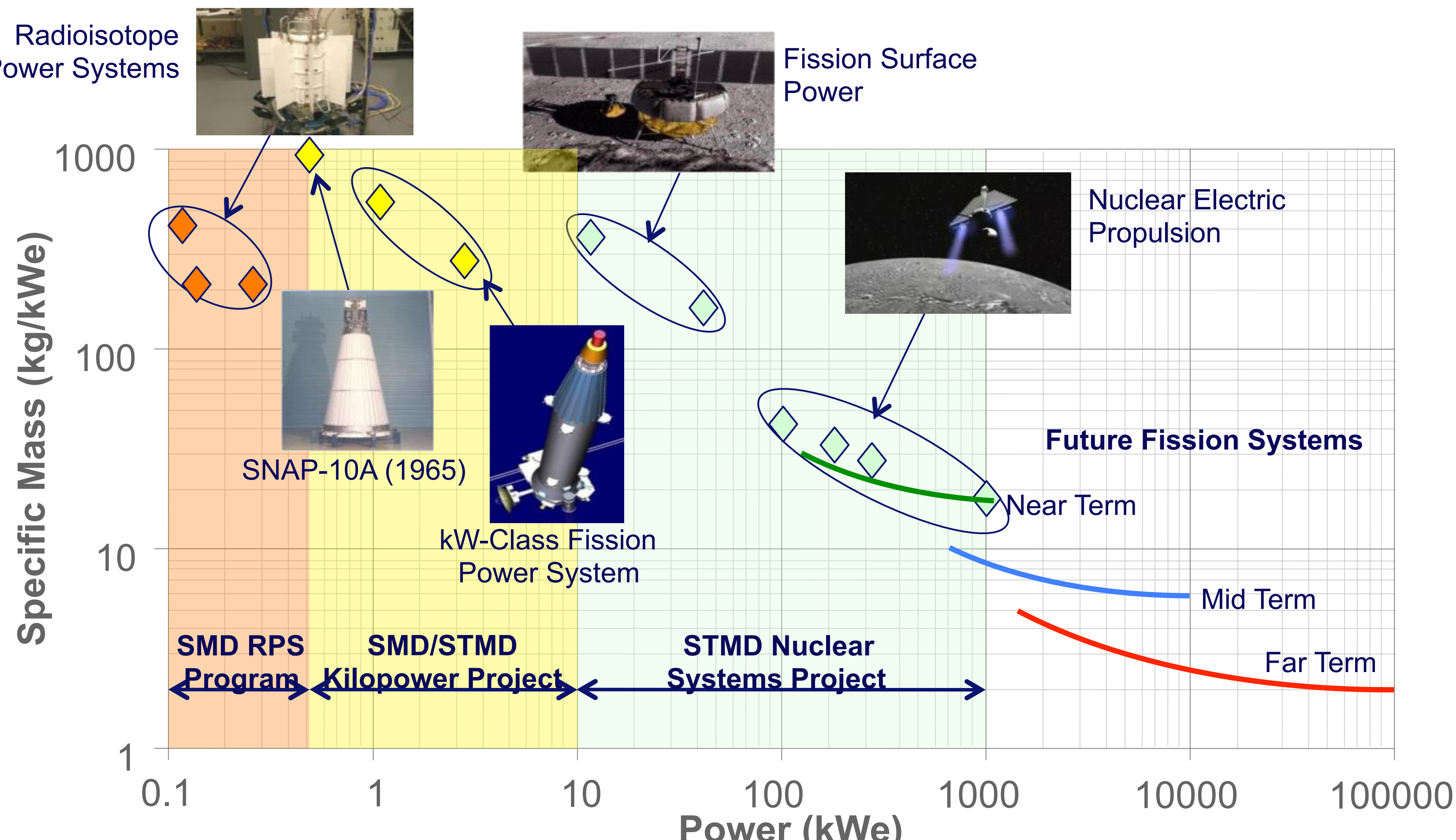


Benefits:

- Lower Reoccurring Costs
- Safer Launches
- Higher Power Missions
- Longer Missions
- Extreme Environments
- Nuclear Electric Propulsion
- Destination Startup

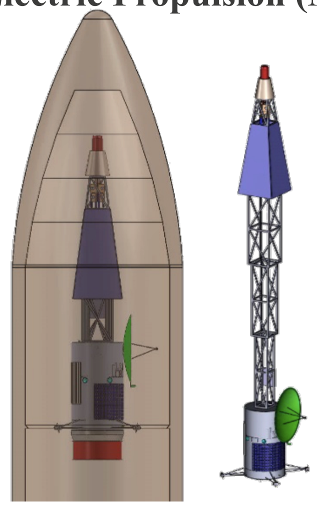


KiloPower Fills Gap in Nuclear Portfolio

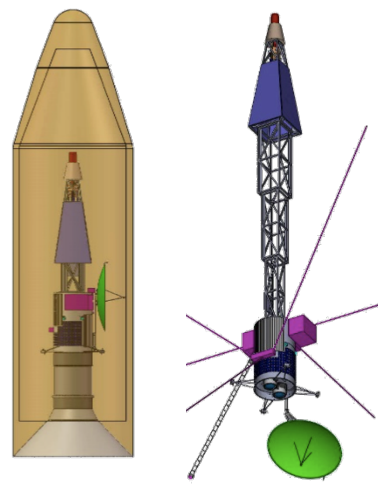


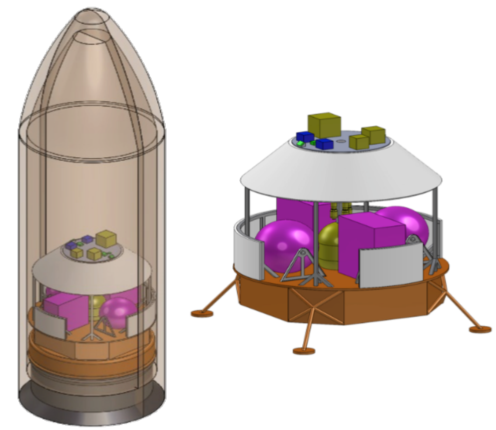
Latest Proposed Missions (latest NASA mission planning)

Chiron Orbiter spacecraft with 8kWe reactor and Nuclear Electric Propulsion (NEP)

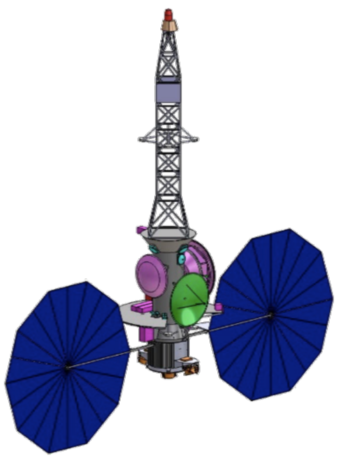


Kuiper Belt Object Orbiter spacecraft with 10kWe reactor and Nuclear Electric Propulsion (NEP)





Mars ISRU fission powered lander concept in LV left, and deployed on Martian surface right



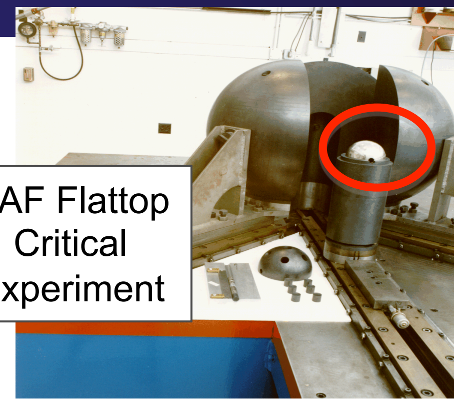
Titan Saturn System Mission spacecraft with attached 1kW fission reactor

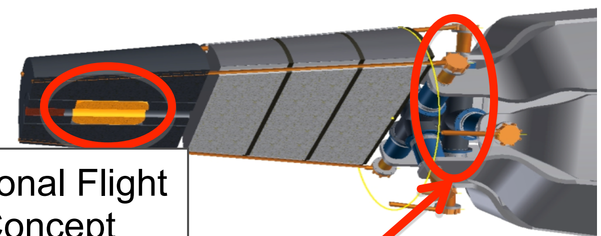
Why this reactor design?

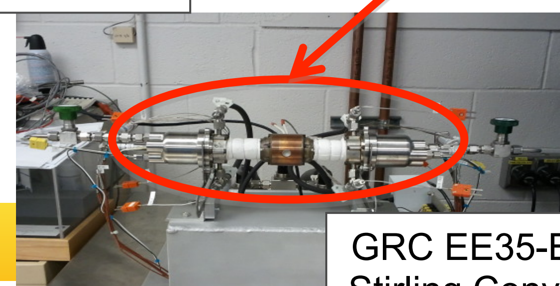
- **Very simple, reliable design**
  - Self-regulating design using simple reactor physics
  - No measurable nuclear effects
  - Small temperature gradients and stresses, and high tolerance to any potential transient
- **Available fuel with existing Infrastructure**
  - Uranium alloy (U-Mo) cast and machined by Y-12 Plant
- **Heat pipe reactors are simple, reliable, and robust**
  - Eliminates components associated with pumped loops; simplifies integration
  - The only reactor startup action is to withdraw reactivity control
- **Systems use existing thermoelectric or Stirling engine technology and design**
- **Low cost testing and demonstration**
  - Non-nuclear system demonstration requires very little infrastructure and power.
  - Nuclear demonstration accommodated in existing facility like those at NCERC.
- **Safe to Launch!**
  - A reactor that has not undergone fission will have from 1 to 10's of curies of naturally occurring radioactivity
  - This is 1,000s to 10,000s times lower radioactivity than in current radioisotope systems

DUFF: A "Critical" Starting Point

- **Proof-of-Concept Test**
- **Test Configuration**
  - Highly Enriched Uranium core with central hole to accommodate heat pipe
  - Heat transfer via single water heat pipe
  - Power generation via two opposed free-piston Stirling Engines
- **Significance**
  - First-ever heat pipe cooled fission experiment
  - First-ever Stirling engine operation with fission heat
  - Demonstration of nuclear reactivity feedback with prototype components
- **Test Objectives**
  - Use electric power generated from nuclear heat to power a load
  - Demonstrate that basic reactor physics was well characterized and predictable using current analytic tools

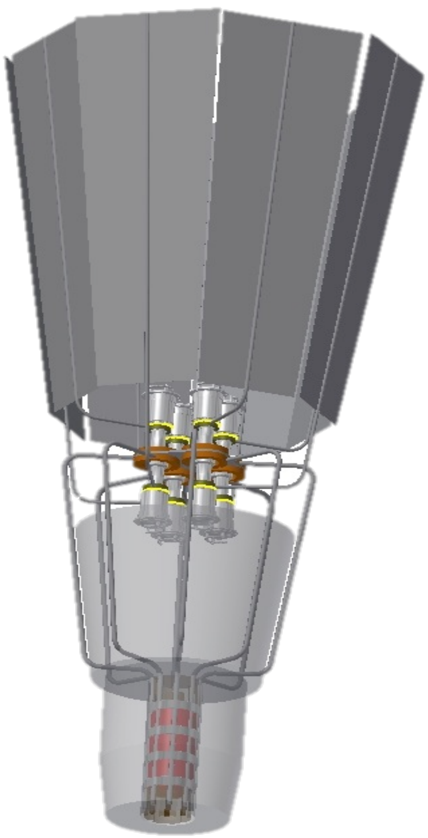




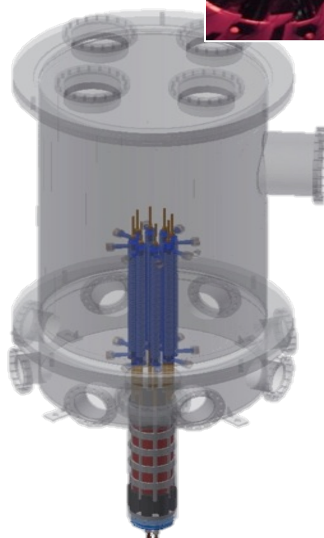


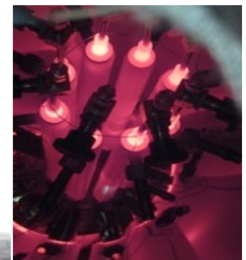
LDRD Funded – Lab investing in technology

Technology Development Strategy

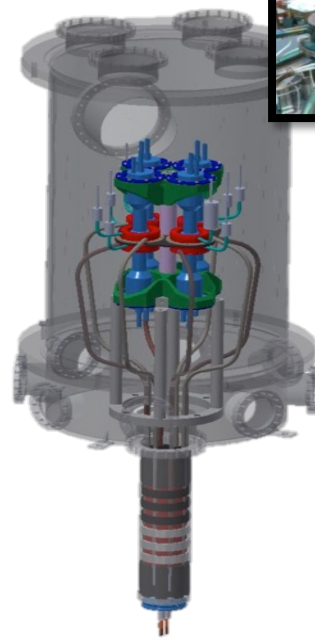


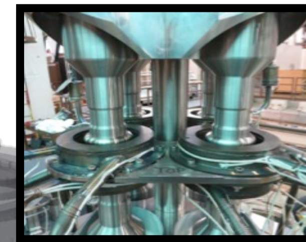
Flight Concept



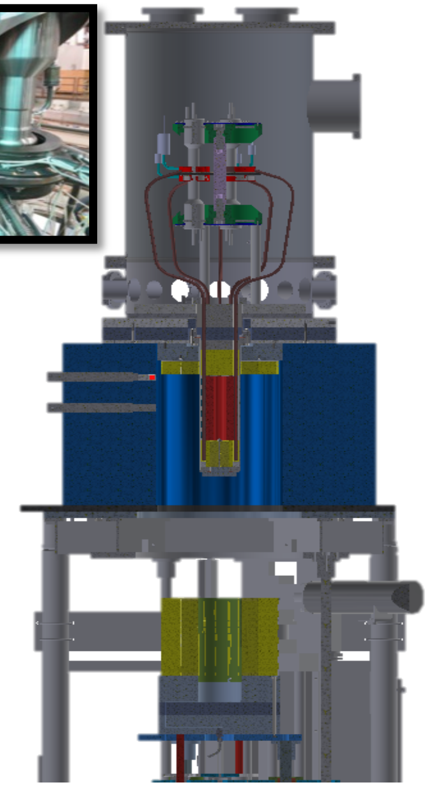


Thermal Prototype & Materials Testing (Year 1)





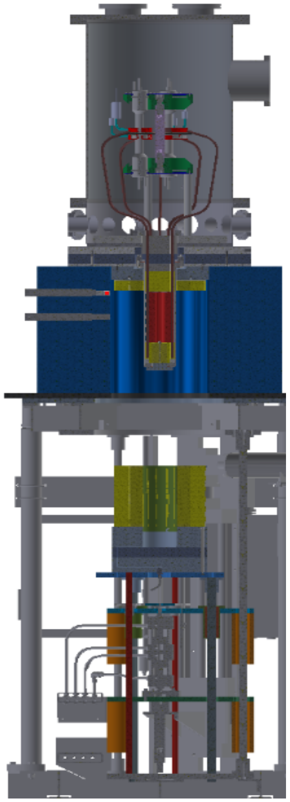
System Test with DU Core and Stirling Convertors (Year 2)



Reactor Experiment with HEU Core (Year 3)

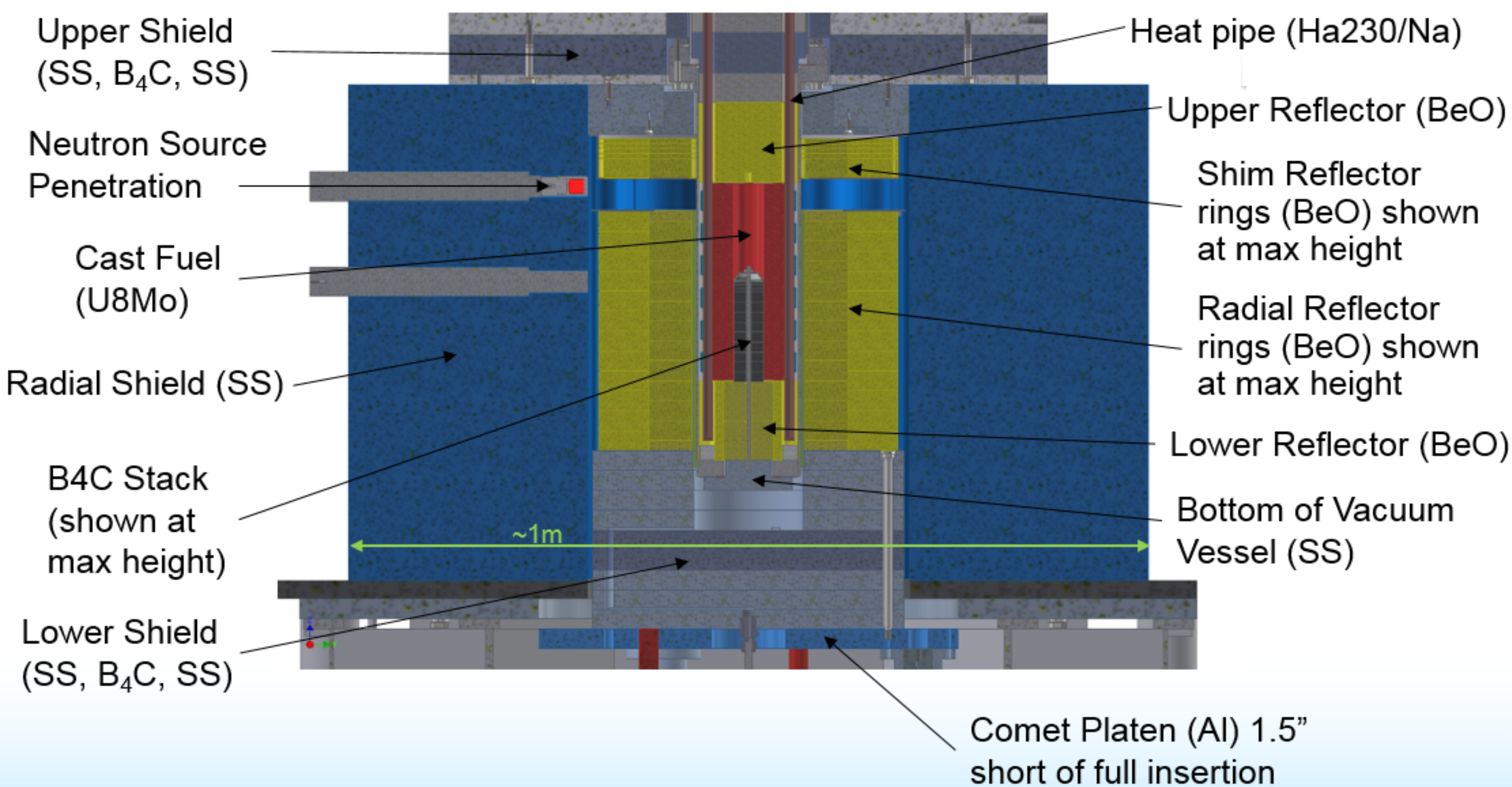
KiloPower Nuclear-Powered Test
(at the Nevada Test Site)

- **Kilopower Reactor Using Stirling TechnologY**
  - Nuclear test of 1-kWe system at NNSA Device Assembly Facility.
  - Extensive electrical testing of system underway at NASA
    - Replaces HEU fuel with DU (depleted in U235)
    - Electrical heater provides simulates fission power and feedback
- **Addresses**
  1. Neutronics/Criticality
  2. Reactor power/feedback
  3. Heat transfer and thermal balance
  4. Startup/shutdown/control operations
  5. Operational stability and robustness to system offsets
  6. Converted electrical power and efficiency
  7. Exercises/demonstrates required flight-like infrastructure

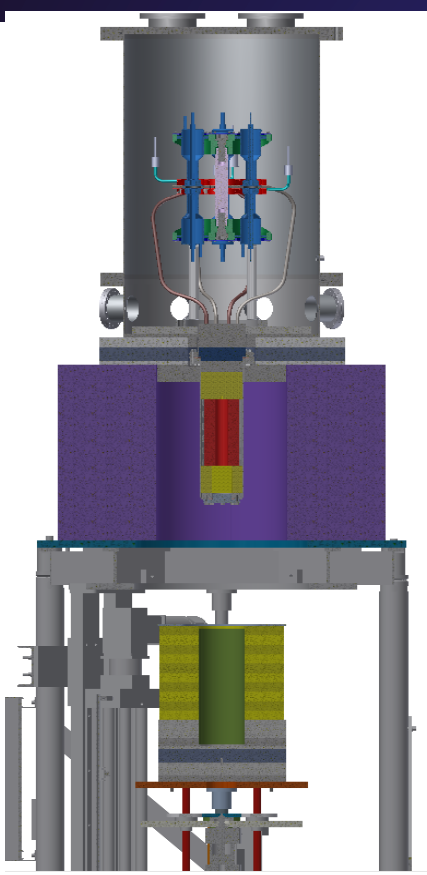


Reflector (yellow) fully withdrawn, leaving fuel (red) and SS shielding (blue) in highly subcritical state

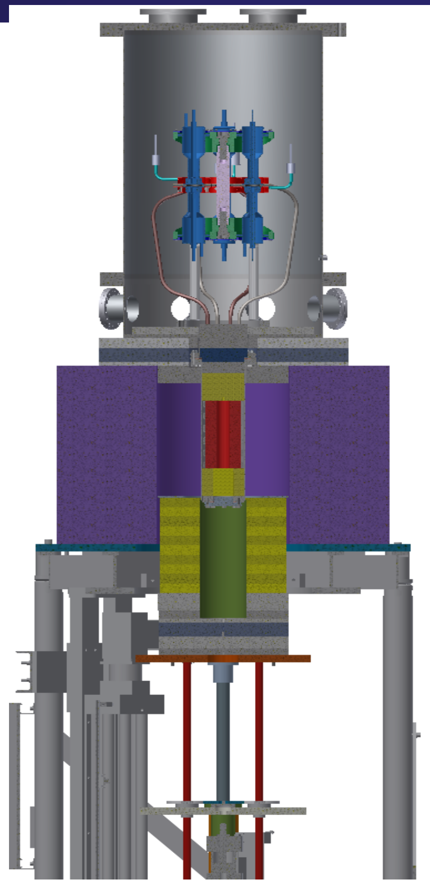
KRUSTY REACTOR CONFIGURATION



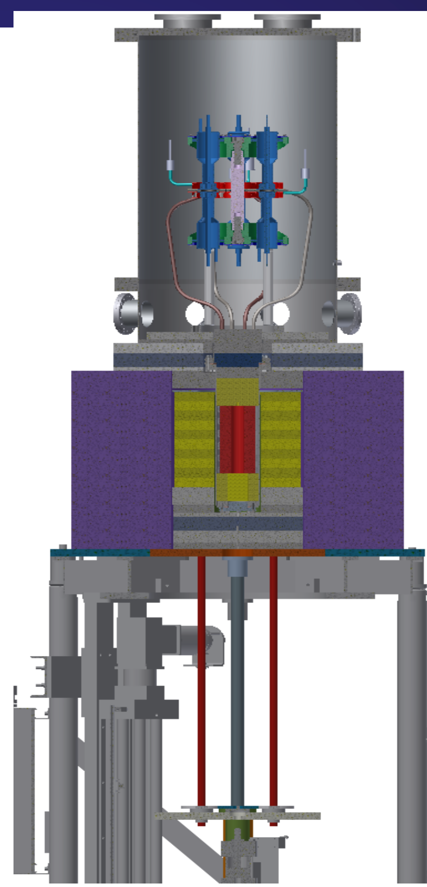
Platen Positions



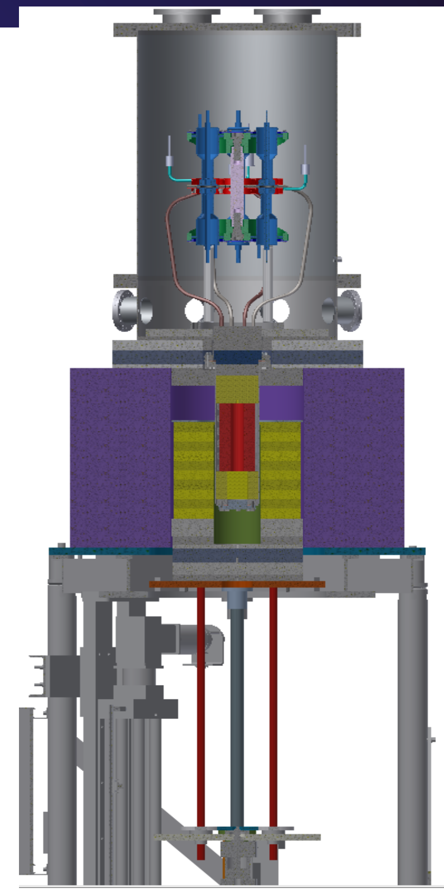
Fully Withdrawn



Neutronically withdrawn

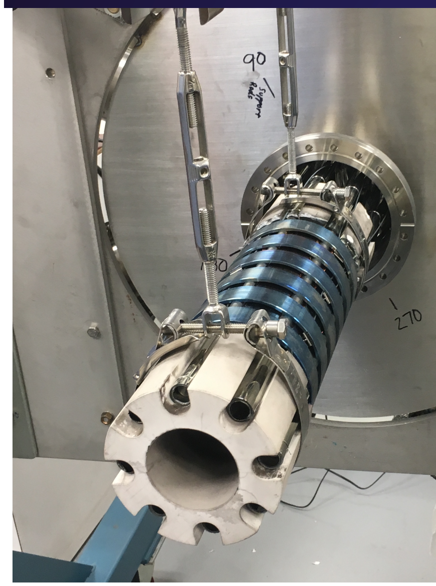


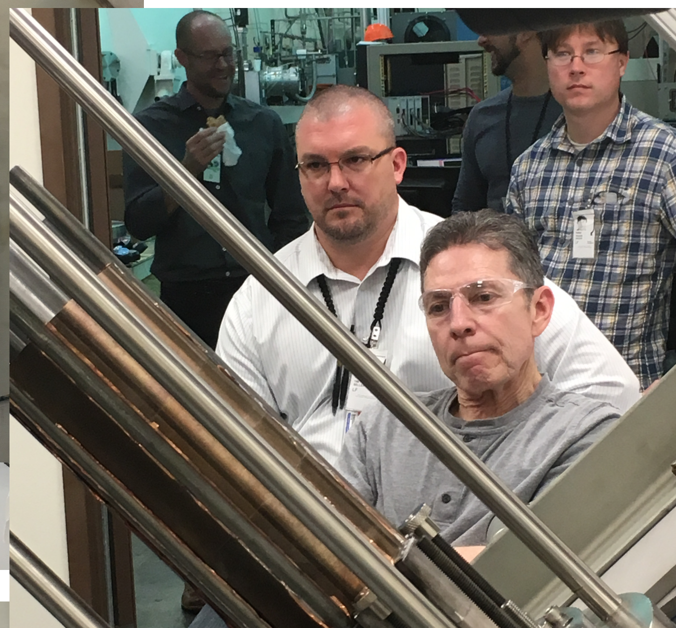
Fully Inserted

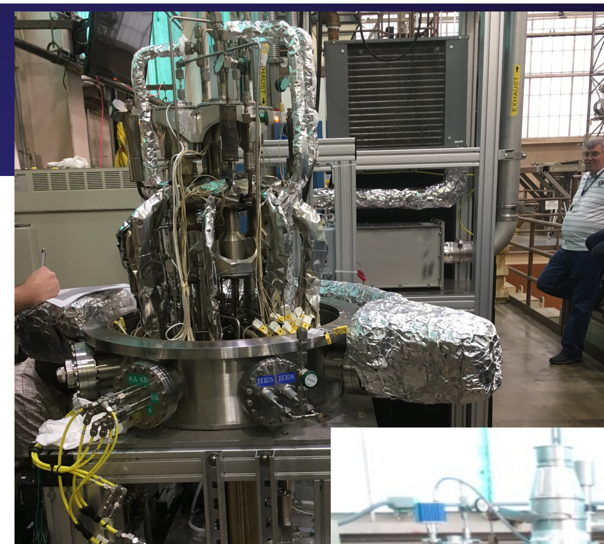


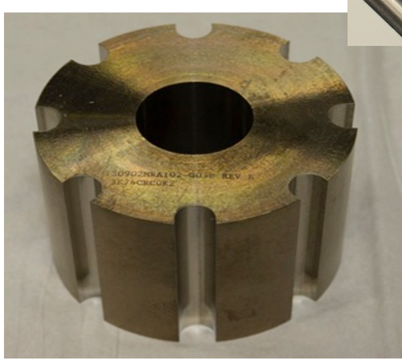
Hydraulic scram
from full insertion

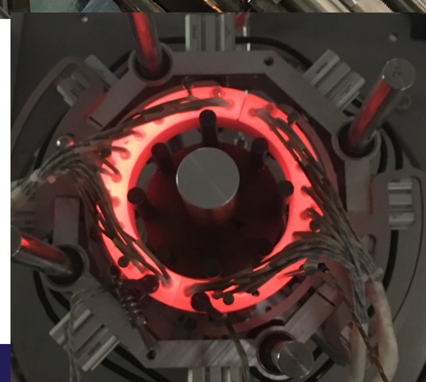
KRUSTY Hardware











1 kW_e KRUSTY Test Retires Many Challenges for 10 kW_e System

- Existing Comet test stand at NNSS
- External heat pipe channels
- 8 perimeter, clamped heat pipes
- Single HP-to-Stirling thermal interface
- Existing Stirling units from RPS

TRL 5 for 1 kW_e

- Prototypic reactor core
- Material properties & compatibility
- UMo fuel casting, machining & inspection
- BeO reflector material & configuration
- Facility controlled reactivity insertion/removal
- Reactivity feedback control
- System performance – start, run, stop, restart
- Nuclear test safety and contingencies
- Nuclear performance code validation

Common Elements

TRL 5 for 10 kW_e

Mars Design

- New test stand at NNSS
- Internal heat pipe channels
- 24 brazed or liquid-metal bonded heat pipes
- Shared HP-to-Stirling thermal bus
- Larger, commercial-adapted power conversion units

Mission Verification

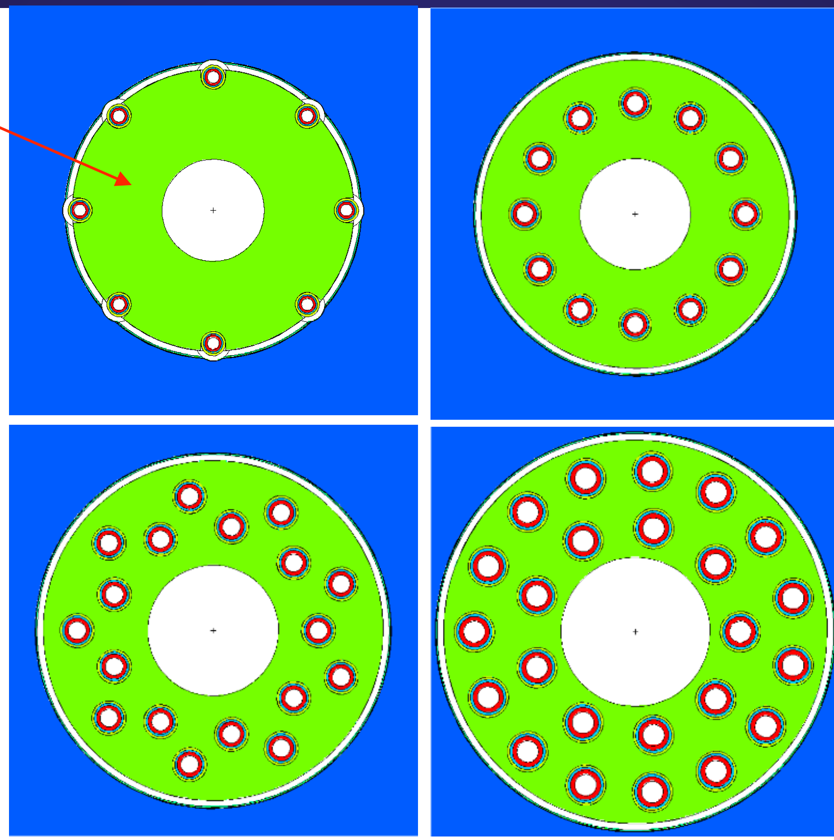
- Mission Interface (e.g. ISRU)
- Prototypic reactor control/shielding
- End-to-end system operations
- Radiation shielding
- Environmental testing
- Nuclear launch safety

TRL 6

Cross sectional view of proposed Kilopower cores (each schematic is 16x16 cm)

KRUSTY is a prototype of this design

kpwr1a:
4.3 kWt
8 3/8” HPs
U235=28 kg
Reactor=134 kg



kpwr1b:
13.0 kWt
12 1/2” HPs
U235=30 kg
Reactor=158 kg

kpwr1c:
21.7 kWt
18 .525” HPs
U235=33 kg
Reactor=184 kg

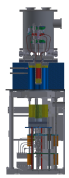
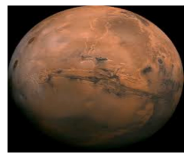
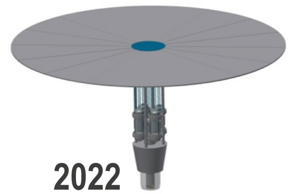
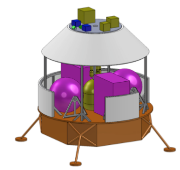
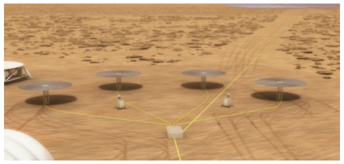
kpwr1d:
43.3 kWt
24 5/8” HPs
U235=43 kg
Reactor 226 kg

Cores are configured so that failed HP peak fuel temp is similar to 4.3 kWt core
Nominal fuel temps are actually much lower in the higher power cores
(each square is 16x16 cm)

Kilopower / KRUSTY Reactor Differences

	Space 1-kWe Kilopower	KRUSTY	Mars 10-kWe Kilopower
Reactivity Control	Central poison rod	Comet lifts reflector	Central poison rod
Operating time	15 years	48 hours?	12 years
Lifetime Reactivity Control	No	n/a	Yes
Fuel/radref separation	1-mm	1-cm (the Divide)	1-mm
Core can/vessel	No	Yes	Yes
Reference heat pipe OD	3/8"	1/2"	5/8"
Heat pipe thermal bonding	Clamp force?	Clamp force	Braze?
U235 mass	28.4 kg	28.0 kg	43.7 kg
Core Length	24 cm	25 cm	28 cm
Shielding	LiH/DU shadow	SS/B4C 4pi	SS/B4C 4pi
Radref temperature	~700 K	<400 K	~700 K
Gravity	0g	1g	.38g
Space Qualification	Yes	No	yes
Launch safety/approval	Yes	No	yes

Notional Timeline – the Big Picture

2017	2020	2022	Mid 2020s	Mid 2030s
KRUSTY Reactor Test (TRL5)	*Mars Power Decision*	*Mars KP System (TRL6)*	*Mars ISRU Pathfinder*	*Crewed Mars Surface*

2017–2020: Full-scale (10 kWe) Reactor & Power Conversion
- DU Core & Heat Pipe Life Test
- Power Conv. Testbeds
- Power Conv. Down-select

2020–2022:
- Fuel Irradiations
- Autonomous Remote Control
- Life Assessment

2022–Mid 2020s: OPTION: NEP Scale-up
- Pin-type Reactor Fuel
- Refractory Alloy Cladding
- High Capacity Heat Transport & Conversion

2017: KP/ISRU Integration Study

2017–2022: Close-coupled KP/ISRU Engr Model Ground Demo (Non-nuclear)
- Electrical/Thermal/Structure Sharing
- e.g. Single Lander/CO2 Chamber

2022–Mid 2030s: OPTION: 1 kWe Space Reactor Flight Demo
- Leverages KRUSTY test
- e.g. Ocean Worlds Ice Surface Penetrator

Mid 2030s: Reactor Ops

2017–2020:
- Mars Requirements
- Solar vs Nuclear Trades (cost, performance, schedule)
- Power System Down-select

2020–Mid 2020s: Mars ISRU Pathfinder Mission
- KP Flight System Development
- Parallel Nuclear Ground Test
- Nuclear Safety/Launch Approval

Mid 2020s–Mid 2030s: Reactor Ops
- Human Rating
- "Utility" Configuration

Mid 2030s: Reactor Ops (w/Crew)

Summary

- **Robust program to develop and deploy a space reactor is in place**
- **Program is well on the way to delivering a major milestone**
  - System testing using nuclear fission
- **Dave Poston will provide the technical details for the design of the experiment**